

5 **LIGHT-COLLECTING ILLUMINATION SYSTEM**

FIELD OF THE INVENTION

 The present disclosure relates to light-collecting illumination systems, which may be used, for example, in projection and backlighting systems. More specifically, the present
10 disclosure relates to illumination systems that collect light from one or more light sources and direct such light toward an illumination target.

BACKGROUND

 Illumination systems have a variety of applications, including projection displays,
15 backlights for liquid crystal displays (LCDs) and others. Projection systems usually include a source of light, illumination optics, an image-forming device, projection optics and a projection screen. The illumination optics collect light from a light source and direct it to one or more image-forming devices in a predetermined manner. The image-forming device(s), controlled by an electronically conditioned and processed digital video signal, produces an
20 image corresponding to the video signal. Projection optics then magnify the image and project it onto the projection screen. White light sources, such as arc lamps, in conjunction with color wheels have been and still are predominantly used as light sources for projection display systems. However, recently, light emitting diodes (LEDs) were introduced as an
25 alternative. Some advantages of LED light sources include longer lifetime, higher efficiency and superior thermal characteristics.

One example of an image-forming device frequently used in digital light processing systems is a digital micro-mirror device (DMD). The main feature of a DMD is an array of rotatable micro-mirrors. The tilt of each mirror is independently controlled by the data loaded into the memory cell associated with each mirror, to steer reflected light and spatially map a pixel of video data to a pixel on a projection screen. Light reflected by a mirror in an ON state passes through the projection optics and is projected onto the screen to create a bright field. On the other hand, light reflected by a mirror in an OFF state misses the projection optics, which results in a dark field. A color image also may be produced using a DMD, e.g., utilizing color sequencing, or, alternatively, using three DMDs, one for each primary color.

Other examples of image-forming devices include liquid crystal panels, such as a liquid crystal on silicon device (LCOS). In liquid crystal panels, the alignment of the liquid crystal material is controlled incrementally (pixel-to-pixel) according to the data corresponding to a video signal. Depending on the alignment of the liquid crystal material, polarization of the incident light may be altered by the liquid crystal structure. Thus, with appropriate use of polarizers or polarizing beam splitters, dark and light regions may be created, which correspond to the input video data. Color images have been formed using liquid crystal panels in the manner similar to the DMDs.

LCD backlights traditionally have included one or more light sources, such as cold cathode fluorescent lamps (CCFLs). Typical direct-lit backlights usually include an array of sources or a single extended source placed behind an LCD. Light generated by the backlight is usually diffused for increased uniformity and directed to an array of red, green and blue filters corresponding to the red, green and blue pixels of the LCD, if a color image is desired.

The red, green and blue pixels modulate the transmitted red, green and blue components according to the input image data.

Performance of optical systems, such as projection and backlighting systems, may be characterized by a number of parameters, one of them being etendue. The etendue, ε , may be
5 calculated using the following formula:

$$\varepsilon = A * \Omega \cong \pi * A * \sin^2 \theta = \pi * A * NA^2$$

where Ω is the solid angle of emission or acceptance (in steradians); A is the area of the receiver or emitter, θ is the emission or acceptance angle, and NA is the numerical aperture.

If the etendue of a certain element of an optical system is less than the etendue of an upstream
10 optical element, the mismatch may result in loss of light, which reduces the efficiency of the optical system. Thus, performance of an optical system is usually limited by the element that has the smallest etendue. Techniques typically employed to decrease etendue degradation in an optical system include increasing the efficacy of the system (lm/w), decreasing the source size, decreasing the beam solid angle, and avoiding the introduction of additional aperture
15 stops.

Traditional optics used in illumination systems have included various configurations, but their off-axis performance has been satisfactory only within narrowly tailored ranges. This and other shortcomings prompted complicated designs of optical elements and systems, which involved, e.g., utilization of complicated aspheric surfaces and complex combinations
20 of numerous elements. In addition, optics in traditional illumination systems have exhibited insufficient collection characteristics. In particular, if a significant portion of a light source's

output emerges at angles that are far from the optical axis, which is the case for most LEDs, conventional illumination systems fail to capture a substantial portion of such light.

Further, traditional illumination systems usually have relatively poor imaging characteristics, for example due to aberrations. In particular, that is the case for most
5 traditional reflectors and/or collectors used in projection and backlighting applications for combining several light sources of different wavelengths. In addition, although some traditional reflective collimators have acceptable collection characteristics, for example, elliptical and parabolic reflectors, such reflectors are usually characterized by rotationally symmetric bias. Such a bias generally results in the rounding of the resultant image as well as
10 in lack of overall correspondence between a point on the light source and a point on the target plane, thus causing loss of order and degradation of etendue.

SUMMARY

The present disclosure is directed to illumination systems including a light source module, a first meniscus lens and a second meniscus lens. The concave side of the second meniscus lens is adjacent to the convex side of the first meniscus lens, and the concave side of the first meniscus lens faces the light source module for receiving light therefrom. The first meniscus lens may be in contact with the second meniscus lens, and the first and second meniscus lenses may be held together by an optically clear material.

Light source modules suitable for use in some exemplary embodiments of the present disclosure include an emitting surface and a substantially optically clear dome disposed over the emitting surface. Light source modules suitable for use in other exemplary embodiments of the present disclosure include an emitting surface and a pyramid collector disposed over the emitting surface. The pyramid collector may have a generally square proximate end and a generally rectangular distal end, but other configurations of the pyramid collector are within the scope of the present disclosure.

Alternatively, light source modules suitable for use in some exemplary embodiments of the present disclosure include a plurality of emitting surfaces disposed next to each other and so that the concave side of the first meniscus lens faces the emitting surfaces of the light source module. At least two of the emitting surfaces may have different colors. For example, exemplary light source modules may have emitting surfaces of first, second and third colors, which could be primary colors.

The present disclosure is also directed to illumination systems including a plurality of light source modules and a system of optical elements, such as a plurality of pairs of meniscus

lenses, each pair being associated with a light source module. The concave side of each second meniscus lens is adjacent to the convex side of each first meniscus lens and the concave side of each first meniscus lens faces the associated light source module. The plurality of the pairs of meniscus lenses may be configured substantially as a double-layered hexagonal or rectangular closely packed array and the plurality of light source modules is disposed to substantially track the configuration of the lenses.

The plurality of the light source modules may be disposed within a non-radially symmetrical aperture. For example, the illumination system including an image-forming device disposed for being illuminated at an angle and having a plurality of mirrors rotatable about a pivot axis, may have a non-radially symmetrical aperture that has a long dimension and a short dimension and is oriented so that the long dimension is aligned with the pivot axis of the mirrors of the image-forming device. Each light source module in such embodiments may include an emitting surface and a substantially optically clear dome or a pyramid collector disposed over the emitting surface.

In the exemplary illumination systems constructed according to the present disclosure that include pyramid collectors, each pyramid collector may have a generally square proximate end and a generally rectangular distal end. However, other configurations of the pyramid collectors are also within the present disclosure. The illumination systems constructed according to the present disclosure may additionally include an illumination target and the system of optical elements may be configured to image the distal end of each pyramid collector onto the illumination target.

In some exemplary embodiments of the present disclosure, the light source modules each have a plurality of emitting surfaces disposed next to each other and so that the concave side of each first meniscus lens faces the emitting surfaces of the associated light source module. At least two of the emitting surfaces may have different colors. For example, 5 exemplary light source modules may have emitting surfaces of first, second and third colors, which could be primary colors. The exemplary illumination systems utilizing such light source modules may additionally include an illumination target having first, second and third color zones, and the system of optical elements may image the emitting surfaces of the first, second and third colors onto the respective color zones of the illumination target. The system 10 of optical elements may also include a lenticular array disposed between the illumination target and the plurality of pairs of meniscus lenses.

These and other aspects of the illumination systems of the subject invention will become readily apparent to those of ordinary skill in the art from the following detailed description together with the drawings.

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BRIEF DESCRIPTION OF THE DRAWINGS

So that those of ordinary skill in the art to which the subject invention pertains will more readily understand how to make and use the subject invention, exemplary embodiments thereof will be described in detail below with reference to the drawings, wherein:

5 Figure 1 is a schematic cross-sectional view of an illumination system constructed according to an exemplary embodiment of the present disclosure;

 Figure 2A is a schematic front view of an array of light source modules with associated optical elements, arranged substantially to approximate the shape of an asymmetric contrast-enhancing aperture;

10 Figure 2B is an enlarged front view of a hexagonal closely packed array of lenses, which may be included in appropriate exemplary embodiments of the present disclosure;

 Figure 3 is an enlarged cross-sectional view of a portion of an illumination system constructed according to an exemplary embodiment of the present disclosure, showing a light source module and associated lenslets;

15 Figure 4A is an enlarged cross-sectional view of a portion of an illumination system constructed according to another exemplary embodiment of the present disclosure, showing a light source module with a pyramid collector and associated lenslets;

 Figure 4B is a schematic front view of the emitting surfaces of an exemplary light source module through the front of an exemplary pyramid collector;

20 Figure 5 is a schematic cross-sectional view of an illumination system constructed according to another exemplary embodiment of the present disclosure, which is particularly useful for backlighting applications;

Figure 6 is a schematic cross-sectional view of an illumination system constructed according to another exemplary embodiment of the present disclosure, which is particularly useful for projection applications;

5 Figure 7 is a schematic representation of a portion of an exemplary embodiment of the present disclosure, illustrating the use of light source modules having emitting surfaces of different colors;

Figure 8 is a schematic cross-sectional view of an illumination system constructed according to an exemplary embodiment of the present disclosure utilizing light source modules having emitting surfaces of different colors; and

10 Figure 9 is a schematic cross-sectional view of an illumination system constructed according to another exemplary embodiment of the present disclosure utilizing light source modules having emitting surfaces of different colors.

DETAILED DESCRIPTION

Referring now to the drawings, wherein like reference numbers designate similar elements, Fig. 1 shows schematically an exemplary embodiment of the illumination systems of the present disclosure, which may be used for projection applications. The illumination system 10 shown in Fig. 1 includes a set of light source modules 12, illustrated by the light source modules 72, 72', 72'', and a system of optical elements 15. One or more light source modules may include an LED light source, such as presently commercially available LED light sources. Those of ordinary skill in the art will appreciate that as LEDs with increased efficiency and output are developed and perfected, such LEDs will be advantageously used in exemplary embodiments of the present disclosure, since LEDs with high maximum output are usually preferred. Alternatively, organic light emitting diodes (OLED), vertical cavity surface emitting lasers (VCSEL) or other suitable light emitting devices may be used.

The set of light source modules 12 may be configured as an array, and the light source modules, such as 72, 72', 72'', may be mounted on one or more substrates, together or individually, so that the heat generated by the light source modules may be readily dissipated by the material of the substrate(s). Examples of substrates suitable for mounting the light source modules include printed circuit boards, such as metal-core printed circuit boards, flexible circuits, such as polyimide film with copper traces, ceramic substrates, and others. Those of ordinary skill in the art will appreciate that many configurations of the set of light source modules 12 and of the individual light source modules, such as 72, 72', 72'', are within the scope of the present disclosure. In addition, the number and type of light source modules

may vary depending on the application, desired system configuration, dimensions of the system, and the system's output brightness.

In the exemplary embodiments illustrated in Fig. 1, the system of optical elements 15 includes a first set of lenses 14, including lenslets 74, 74', 74'', a second set of lenses 16, including lenslets 76, 76', 76'', and a condenser 18. Similar to the number of light source modules, the numbers of lenslets in the sets 14 and 16 may vary depending on the application, the desired system configuration and the desired dimensions of the system. The condenser 18 may be or may include a plano-convex lens. Alternatively, the condenser may be or may include a meniscus lens in order to reduce aberrations, or any other type of lens or lenses depending on the desired characteristics of the output light. The system of optical elements 15 may include other components in addition to or in place of the condenser 18, as may be useful for a particular application, for example it may include dichroic mirrors for separating or combining light beams of different colors.

In the appropriate embodiments of the present disclosure, each light source module has an optical element or elements associated with it in order to facilitate collection of light and to achieve the desired imaging characteristics. For example, in the exemplary embodiment illustrated in Fig. 1, a pair of lenslets (one from the set 14 and one from the set 16) is associated with each light source module from the set 12. In particular, Fig. 1 shows lenslets 74 and 76 associated with the light source module 72, lenslets 74' and 76' associated with the light source module 72', and lenslets 74'' and 76'' associated with the light source module 72''. The sets of lenses 14 and 16 may be configured as a double-layered closely packed array with the configuration substantially tracking the configuration of the set of light source modules 12.

An exemplary configuration of the set of light source modules is illustrated in Fig. 2A, which shows a theoretical circular entrance pupil 2 of an illumination system and a non-radially symmetrical aperture 4, representing the entrance pupil, formed by appropriately positioning the set of light source modules 12'. This and similar configurations are particularly advantageous in projection systems utilizing one or more DMDs illuminated at an angle and without a light tunnel (described below) being interposed between the light source and the image-forming device. Generally, in such systems there is a strong dependence between the angle of illumination and the amount of light scattered into a projection pupil by reflection from the mirror frame, from beneath the mirrors in OFF states, and from the mirrors in flat or transitional states. Increasing illumination angle increases contrast, but it also causes an offset of the illumination pupil with respect to the projection pupil, introducing vignetting, if the numerical aperture of the projection optics is not increased accordingly. However, if the projection optics' aperture is increased to avoid vignetting, it can collect more flat state or transitional (neither ON nor OFF) reflections and stray light from around the DMD and pass it on to the screen, thus potentially defeating the initial intent of improving contrast.

In the traditional illumination systems utilizing arc lamps, this problem was addressed by placing a truncating aperture stop in the illumination pupil to block at least a portion of the flat state reflections that overlap with the ON state reflections. However, recently, it has been shown that the contrast of DMD projection systems can be enhanced with asymmetric aperture stops. U.S. Patent No. 5,442,414, the disclosure of which is hereby incorporated by reference herein to the extent it is not inconsistent with the present disclosure, describes

contrast-enhancing asymmetric apertures, having long and short dimensions, with the long dimension being aligned with the pivot axis of the mirrors.

Thus, in the appropriate exemplary embodiments of the present disclosure, the configuration of the set of the light source modules 12' may be selected so that the individual light source modules are disposed substantially within the area of the pupil that has the highest contrast, illustrated as the non-radially symmetrical aperture 4, thereby conserving illumination energy and reducing the number of the light source modules used. The configuration of the set of optical elements 13, associated with the light source modules, may be selected accordingly, and preferably will track the configuration of the set of the light source modules 12', so that the latter also would have the general shape substantially approximating a non-radially symmetrical aperture, as illustrated in Fig. 2A. Other configurations of the sets of light source modules and the sets of optical elements, for example sets of lenses 14 and 16 shown in Fig. 1, are also within the scope of the present disclosure, such as arrays having generally rectangular or square shape, depending on the specific application and other considerations, such as the shape and size of the illumination target, as well cost.

Fig. 2B represents a front view of an exemplary configuration 58 of the sets of lenses 14 and 16. In the configuration 58, lenslets of the set of lenses 14, such as 74, 74', 74'', may be substantially the same shape and size, for example, having a substantially round outside diameter of about 18 mm. Lenslets of the set of lenses 16, such as lenslets 76, 76', 76'', also may have substantially the same shape and size, for example, a substantially hexagonal shape with the shorter diagonal of about 20 mm and the longer diagonal of about 23 mm. The outer

dimensions of the lenslets from the set 14 should be sufficiently large to collect a desired amount of light from the set of light source modules 12 and the outer dimensions of the lenslets from the set 16 should be sufficiently large to capture a desired amount of light exiting the set 14. In some exemplary embodiments, the individual lenslets in the sets 14 and 16 may have the same general shape and configuration, except for the edge details, since the second array preferably should be tooled to minimize interstitial areas.

The lenslets of the sets 14 and 16, such as lenslets 74, 74', 74'' and 76, 76', 76'', preferably are meniscus lenses configured substantially as the lenslets 74 and 76 shown in Fig. 3. Fig. 3 also shows a light source module 72, which in this exemplary embodiment includes a base 722, an emitting surface 724 and a substantially optically clear dome 726.

Commercially available LED light source modules may be used in the appropriate embodiments of the present disclosure, which would make such illumination systems relatively inexpensive, compact and convenient to use. The emitting surface 724 may be or may include an emitting surface or surfaces of an LED, a layer of phosphor, or any other emissive material. Those of ordinary skill in the art will understand that the term "emitting surface" may be used to refer to any light-emitting surface of a light source module, such as any surface portion of a light-emitting semiconductor layer or chip encapsulated into substantially optically clear material.

As one example, dimensions of the lenslets 74 and 76 include a center thickness of about 8.8 mm, about -55 mm radius of the concave surfaces, and aspheric convex surface (described by the general aspheric equation) with the radius of about -10 mm and with a conic constant of about -0.55. The convex surface is made aspheric in order to reduce aberrations

and to avoid the resulting loss of light. Optionally, the concave surface may be made aspheric as well. However, the performance of such lenses is more strongly influenced by the shape of the convex surface. Nonetheless, those of ordinary skill in the art will readily appreciate that the overall shape and size of the lenslets may vary depending on the specific application,
5 configuration of the system and the system's size. The material of the lenses is preferably acrylic, but polycarbonate, polystyrene, glass or any other suitable material may be used as well. In general, materials with higher indexes of refraction are preferred, but ultimately the choice will be made depending on the factors important for a particular application, such as cost, moldability, ease of refractive index matching with optical glues or epoxies, etc.

10 In the appropriate embodiments of the present disclosure, the lenslet 74, having a concave side 74a and a convex side 74b, is disposed before the light source module 72, so that the concave side 74a generally faces the emitting surface 724. The lenslet 76, having a concave side 76a and a convex side 76b, is disposed so that the concave side 76a is adjacent to the convex side 74b. Preferably, the concave side 76a of the lenslet 76 is in direct contact
15 with the convex side 74b of the lenslet 74 in order to maximize light collection efficiency, but in some embodiments the lenslets may be separated by a distance of up to about 4 mm and still have acceptable light collection characteristics. Larger spacings are also within the present disclosure, but such configurations are likely to have decreased collection efficiency if the spacing is increased without also increasing the outer dimensions of the lenslet 76. It will
20 be understood by those of ordinary skill in the art that placing the lenslets 74 and 76 closer together and increasing the diameter of the lenslet 76 will usually allow collection of light

within a wider range of angles and vice versa. The lenslets may be held together by a suitable optical glue or epoxy that is substantially index matched to the material of the lenslets.

Referring further to Figs. 1 and 3, in some exemplary embodiments of the present disclosure, the system of optical elements 15 images one or more of the emitting surfaces of the light source modules, for example, the emitting surface 724 of the light source module 72, onto an illumination target 17. The nature of the illumination target 17 will vary depending on the specific application. For example, in Fig. 1, the illumination target 17 is shown, for illustrative purposes only, to be an entrance to a light tunnel 19.

Light tunnels suitable for use with the appropriate exemplary embodiments of the present disclosure are described, for example, in U.S. Patent Nos. 5,625,738 and 6,332,688, the disclosures of which are hereby incorporated by reference herein to the extent they are not inconsistent with the present disclosure. A light tunnel would serve to homogenize the output of the light emitting modules, such as 72, 72', 72'', and thus precise imaging of the emitting surfaces would not be needed in the exemplary embodiments utilizing light tunnels. The light tunnel 19 may be a mirror tunnel, e.g., a rectangular tunnel, solid or hollow, or an elongated tunnel composed of a solid glass rod that relies on total internal reflection to transfer light through it. Those of ordinary skill in the art will appreciate that numerous shape combinations for the input and output ends of the light tunnels are possible.

In other exemplary embodiments, the illumination target 17 may be an image-forming device, e.g., a DMD, a liquid crystal panel or one or more pixels or color zones of a liquid crystal display. In such embodiments, more precise imaging may be desired. In addition, such embodiments, if used in projection systems utilizing one or more DMDs, would benefit

from arranging the light source modules to approximate substantially the shape of the contrast-enhancing asymmetric aperture, illustrated in Fig. 2A.

The emitting surfaces of the light source modules, such as those of the light source modules 72, 72', 72'', can be given a specific shape to improve the performance of the illumination system 10. For example, one or more of the emitting surfaces may be shaped to match substantially the shape of the target 17. In particular, if the target 17 is a square entrance to a light tunnel 19, one or more of the emitting surfaces of the light source modules may also be generally shaped as squares. If, on the other hand, the target 17 is a rectangular image-forming device having an aspect ratio of about 16:9 (which is usually the case in high definition televisions), one or more of the emitting surfaces of the light source modules may also be generally shaped as rectangles, preferably with about the same aspect ratios. Alternatively, images of generally square emitting surfaces may be closely packed to substantially fill a generally rectangular illumination target. It will be readily appreciated by those of ordinary skill in the art that other general shapes of the emitting surfaces and of the illumination targets are within the scope of the present disclosure.

Referring further to Fig. 1, the system of optical elements 15 may be designed and configured to appropriately magnify the images of the emitting surfaces. Performance of a typical projection display usually would benefit from, or in some cases even require, a certain amount of overfill of the illumination target by the illumination patch, which in these exemplary embodiments would be formed by the superimposed images of one or more emitting surfaces of the light emitting modules. For example, for an imaging device of about 20.0 x 12.0 mm, the illumination patch may be about 10% larger in each axis, or about 22.0 x

13.2 mm. In some exemplary embodiments, it is desirable to make the amount of overfill substantially the same on all sides, for example, to accommodate mechanical misalignments. In such cases, one or more of the emitting surfaces of the light surface modules may be made slightly different in aspect ratio from the illumination target, in order to produce an image of the desired shape. Alternatively, the system of optical elements may include cylindrical lenses or other non-circularly symmetric optics that could convert the image(s) of the emitting surface(s) to a desired general shape or aspect ratio. Also, when desired, images of emitting surfaces of different colors, such as red, green and blue, or other primary colors, may be combined or superimposed with dichroic combining mirrors as shown and explained below.

Fig. 4A shows another exemplary configuration of a light source module suitable for use in the appropriate embodiments of the present disclosure. The light source module 82, shown in Fig. 4A, includes a base 822, one or more emitting surfaces, for example emitting surface 824, and a short pyramid collector 827 mounted over the emitting surface 824. The short pyramid collector 827 preferably is a substantially optically clear article, for example made of acrylic, polycarbonate, glass or another suitable material, the sides of which operate as simple reflectors for the light emanating from the one or more emitting surfaces at angles that are sufficiently large to result in total internal reflection of such light within the pyramid collector.

If the emitting surface 824 is an emitting surface of an LED (which may have several emitting surfaces, i.e., several LED dies) the pyramid collector 827 preferably is placed over the emitting surface or surfaces and attached to the base 822 by a suitable substantially optically clear cementing material or molded directly onto it, so that it is in contact with and

covers the entire emitting surface 824 or the multiple emitting surfaces of the light source module 82. The cementing material should be selected depending on the refractive index of the material of the pyramid collector. If the refractive index of the cementing material is higher than the refractive index of the pyramid collector material, a significant portion of emitted light may be lost due to reflections at their interface. Thus, preferably, the refractive index of the cementing material substantially matches or is slightly lower than the refractive index of the pyramid collector in order to facilitate more efficient light collection. Minimization or removal of an air gap between the emitting surface of an LED and the pyramid collector also enhances collection efficiency.

Fig. 4B shows the emitting surfaces of a light source module, exemplified by the emitting surface 824, viewed through the front of the pyramid collector 827, which in this exemplary embodiment has a generally square proximal end 825 facing the emitting surface 824 and a generally rectangular distal end 829 facing away from the emitting surface 824. For an emitter with the generally square outer shape with a side of about 1 mm, such as the active surface of an InGaN LED, exemplary suitable dimensions of the pyramid collector 827 include a generally square proximal end 825 with the side of about 1 mm, a generally rectangular distal end 829 of about 4.3 mm by 2.4 mm, and the height of the pyramid collector (the distance between the proximal and distal ends) of about 4 to 5 mm.

In some embodiments of the present disclosure, the outer dimensions and shape of the proximal end 825 are matched to the dimensions and shape of the emitter and fitted around the emitting surface or surfaces, while the distal end 829 should be a larger rectangle, for example with the aspect ratio of about 16:9 (which is particularly useful for HDTV

applications). Alternatively, the distal end 829 may have a generally square shape, and in the appropriate exemplary embodiments such light source modules may be stacked to form a generally rectangularly shaped illuminator, with the associated optics substantially tracking that configuration. Those of ordinary skill in the art will readily appreciate that other suitable dimensions and configurations of the pyramid collectors are within the scope of the present disclosure, depending on the dimensions and shape of the emitting surface, dimensions and shape of the collecting optics, such as the lenslets 84 and 86, and other relevant system parameters.

The use of a pyramid collector, such as the pyramid collector 827, is particularly advantageous where the emitting surface 824 is an emitting surface of an LED that does not appear sufficiently uniform or where a square emitting surface needs to be reshaped, for example, to match a rectangular illumination target or a rectangular color zone or pixel. In addition, the pyramid collector 827 could redirect at least some of the light emanating from the emitting surface 824, so that it would exit the pyramid collector 827 at smaller angles with respect to the optical axis and thus would be easier to collect by the downstream optical elements, such as the lenses 84 and 86. In some exemplary embodiments of the present disclosure, a pyramid collector placed atop an LED emitting surface allows the collection of as much as about 70% of the total amount of light emitted by the LED into about 88% of the etendue value. However, in various exemplary embodiments of the present disclosure other relations of the collection efficiency and etendue may be deemed desirable, depending on the size and type of the individual components, the overall configuration of the system, as well as cost considerations. Furthermore, the far-field output of the pyramid collector 827 forms a

pattern that may be closely packed (with some overlap, if desired) with others to form a combined illumination field, which is particularly useful in projection and backlighting applications.

Referring further to Figs. 1 and 4A, in some exemplary embodiments of the present disclosure, the system of optical elements 15 images one or more of the emitting surfaces of the light source modules, for example, the emitting surface 824 of the light source module 82, onto an illumination target 17. This case is illustrated in Fig. 4A by the ray 1 traced through the pyramid collector 827. As illustrated in Fig. 4B, at least a portion of the light emanating from the emitting surface 824 is reflected by the sides of the pyramid collector 827. Such reflected light causes the image of the emitting surface 824 to be multiplied resulting in an array of LED images, such as the images 824a, 824b, 824c and 824d, schematically shown in Fig. 4B. If the proximal end 825 of the pyramid collector 827 is fitted substantially around the emitting surface 824, then the array of images is closely packed as viewed through the distal end 829.

Thus, in some exemplary embodiments, it is advantageous to image the distal end 829 of the collector pyramid 827 onto the illumination target 17. This case is illustrated in Fig. 4A by the ray 2 traced through the pyramid collector 827, in such a way that it is reflected from the pyramid's side. Imaging the distal end 829 instead of the emitting surface itself allows the emitting surface to retain its original shape, such as a square or a collection of stripes for typical commercially available LEDs, and the pyramid collector will effectively create a rectangular pattern of light that may then be imaged onto a rectangular illumination target without the need for homogenizing and reshaping by additional optics. In addition, this

configuration aids in conserving etendue, because the illumination angles are reduced proportionately to the increase of area from the proximal to the distal ends of the pyramid collector.

Another exemplary embodiment of the illumination systems of the present disclosure is illustrated in Fig. 5. Such exemplary embodiments may be used for direct backlighting of LCDs. In particular, the illumination system 30 shown in Fig. 5 may be used to illuminate an LCD 85. The illumination system 30 includes a set of light source modules 32, such as light source modules 72, 72', 72'', which may be LED light source modules, and a system of optical elements 35. In such exemplary embodiments, sufficient amount of light source modules, such as 72, 72', 72'', should be used to create an illumination patch that covers a sufficient portion of the surface of the LCD 85, to obtain a resultant image of the desired size, brightness and quality. In such exemplary embodiments, the system of optical elements 35 includes a first set of lenses 34, including lenslets 74, 74', 74'', a second set of lenses 36, including lenslets 76, 76', 76'', and may further include collimating optics such as Fresnel lenses, gradient index lenses, etc. It will be understood by those of ordinary skill in the art, that the system of optical elements 35 may include other additional components as may be desired for a particular application.

Referring further to Fig. 5, in the appropriate embodiments, a pair of lenslets, one from the set 34 and one from the set 36, for example, lenslets 74 and 76, may be associated with each light source module, for example, 72. The sets of lenses 34 and 36 may be configured as a double-layered closely packed array, similar to the array shown in Fig. 2B, in which the number and overall structure of the configuration 58 is altered to accommodate the desired

number of the light source modules 72, 72', 72'', etc. and the shape of the surface to be illuminated, such as the LCD display 85, which is usually generally rectangular or square.

The general shapes and respective positioning of the lenslets in the sets 34 and 36, as well as the general shape and positioning of the light source modules may be substantially the same as

5 those described in reference to the embodiments illustrated in Figs. 1-4B or have another suitable configuration.

The system of optical elements 35 may be configured so that it images one or more of the emitting surfaces of the light source modules of the set 32 onto one or more pixels, such as 850, 850', 850'', of the LCD 85, which in these exemplary embodiments would constitute the
10 illumination target or targets (see Fig. 1, element 17). In some exemplary embodiments, it is preferable to image the emitting surfaces onto the LCD 85 with at least some amount of overlap of the adjacent images to create a substantially continuous illumination patch. Thus, in such embodiments, images of the emitting surfaces overlap, or at least partially overlap, to compose a substantially uniform pattern from many emitters, wherein the individual elements
15 may have non-uniform shapes. Further, in the exemplary embodiments suitable for direct view backlighting, the images may have only a small amount of overlap, just so that they substantially fill the area to be illuminated. Here, substantial superposition of the images is not needed, as would be the case for most projection applications. Alternatively, an individual emitting surface may be imaged onto a discrete pixel or a certain number of pixels.

20 Alternatively, the system of optical elements 35 may collect and process light from the set of light source modules 32, so that the light enters the LCD 85 in a substantially collimated state. In such embodiments of the present disclosure, when the LCD 85 is viewed

off-axis, a diffuser, scattering medium or another enhancement component 87 may be added to enhance off-axis viewability, either under or over the LCD 85. Those of ordinary skill in the art will readily appreciate that other display components also may be added as desired for a specific application. Further, in the illumination system 30, a tradeoff may be made between the brightness of the light source modules, their size and the number of channels (here, the number of individually controlled sources with the associated optics).

Another exemplary embodiment of the illumination systems of the present disclosure is illustrated schematically in Fig. 6. Such an illumination system 40 may be used in a projection system 150. The illumination system 40, used to illuminate a projection screen 154, includes a set of light source modules 42, such as light source modules 72, 72', 72'' (as in Figs. 1-5), and a system of optical elements 45. In the exemplary embodiments illustrated in Fig. 6, the system of optical elements 45 includes a first set of lenses 44, having lenslets similar to those shown and described in reference to Figs. 1-5, and a second set of lenses 46, also having lenslets similar to those shown and described in reference to Figs. 1-5. The illumination system 40 may be followed by an imaging device 141, such as an LCD transmissive device, and by a field lens 143, such as a Fresnel lens. Folding mirrors 145, 149 and 152, which may be ordinary front-surface mirrors, may be used for folding the optical path of the projection system 150 and thus increasing its compactness. The projection system may further include projection optics 147 for projecting the image created by the imaging device 141 onto the screen 152.

Referring further to Fig. 6, a pair of lenslets, one from the set 44 and one from the set 46, for example, lenslets 74 and 76 shown in Fig. 3, may be associated with each light source

module, for example, 72, also shown in Fig. 3. The sets of lenses 44 and 46 may be configured as a double-layered closely packed array, similar to the array shown in Fig. 2B, in which the number and overall structure of the configuration 58 may be altered to achieve the desired brightness, resolution and size of the resultant image formed on the screen 154.

5 Preferably, the general shapes and sizes of the lenslets of the sets 44 and 46, as well as the general shape and size of the light source modules of the set 42, are substantially the same as those described in reference to the embodiments illustrated in Figs. 1-5. Exemplary
embodiments illustrated in Fig. 6 are particularly useful for large LCD panel projection
applications, because they allow decreasing the size of the cabinet and using fewer
10 components.

In accordance with another aspect of the present disclosure, Fig. 7 illustrates a light source module having emitting surfaces of multiple colors. For example, in Fig. 7, the light source module 172 includes three emitting surfaces 194R, 194G and 194B (red, green and blue, respectively, or other suitable primary colors), placed next to each other. Such light
15 emitting modules may be three-chip LED modules, and any one or more of the emitting surfaces may be or include LED emitting surfaces, phosphor layers, or any other emissive materials. Collimator optics 174 and 176 may include lenslets similar to those shown and described in reference to the embodiments illustrated in Figs. 1-6 or any other suitable optical elements. Preferably, each lenslet receives light from all three emitting surfaces 194R, 194G
20 and 194B. Thus, the cost and size of illumination systems may be decreased, because multiple light sources share the same optics. To accomplish this, the emitting surfaces 194R, 194G and 194B should be disposed sufficiently close together. In addition, the emitting

surfaces should be disposed sufficiently close to the lenslets to ensure efficient collection of light.

The light source module 172 and the collimating optics 174, 176 are configured so that collimation is achieved for the emitting surfaces 194R, 194G and 194B in such a way that the illumination is “indexed” with respect to a particular color. This may be accomplished by placing the emitting surfaces 194R, 194G and 194B near the focal plane of the collimating optics, so that spatial separation of the different color emitters is transformed into angular separation of the beams having different colors. For example, for an arrangement shown in Fig. 7, green light may exit the collimating optics at about 0 degrees to the optical axis, while red light may exit the collimating optics at about +2 degree angle to the optical axis, and blue light may exit at about -2 degree angle.

Fig. 8 schematically shows another exemplary embodiment of the illumination systems of the present disclosure. The illumination system 100 shown in Fig. 8 includes a set of light source modules 112, such as light source modules 172, 172' and 172'', each having multiple emitting surfaces 194R, 194G, 194B, 194R', 194G', 194B' and 194R'', 194G'', 194B'' respectively, and a system of optical elements 115. In the exemplary embodiments illustrated in Fig. 8, the system of optical elements 115 includes a first set of lenses 114, including lenslets 174, 174', 174'', a second set of lenses 116, including lenslets 176, 176', 176'', dichroic mirrors 120R, 120B and 120G and a condenser 118. The condenser 118 may be or may include a plano-convex lens, preferably having an aspheric convex surface, a meniscus lens, or a gradient-index lens. The system of optical elements 115 may include other

components in addition to or in place of the elements shown, as may be desired for a particular application

In the appropriate embodiments of the present disclosure, the set of lenses 114 including lenslets 174, 174', 174'' and the set of lenses 116 including lenslets 176, 176', 176'' may have configurations similar to the sets of lenses described in reference to other exemplary embodiments of the present disclosure, or they may have other suitable configurations, as appropriate for a particular application. For example, a pair of lenslets, one from the set 114 and one from the set 116 may be associated with each light source module. For example, in Fig 8, lenslets 174 and 176 are associated with the light source module 172, lenslets 174' and 176' are associated with the light source module 172'', and lenslets 174'' and 176'' are associated with the light source module 172'''. As it was explained in connection with Fig. 7, any or all of the emitting surfaces 194R, 194G, 194B, 194R', 194G', 194B' and 194R'', 194G'', 194B'' may be emitting surfaces of red, green and blue (RGB) LED modules, layers of phosphor, any other emissive material or any number or a combination thereof.

Referring further to Fig. 8, the system of optical elements 115 may be configured to image one or more of the emitting surfaces of the light source modules, for example, 172, 172', 172'', onto an illumination target 117. As it has been explained in reference to other exemplary embodiments, the nature of the illumination target 117 will vary depending on the specific application. For example, the illumination target 117 may be an entrance to a light tunnel, an imaging device, an LCD, or a specific color zone or pixel of an LCD. Where superimposed or at least partially overlapping color illumination patches are desired, dichroic

mirrors 120R, 120B and 120G may be used to combine the images of emitting surfaces of different colors on the illumination target 117.

Similar to other exemplary embodiments described herein, one or more of the emitting surfaces 194R, 194G, 194B, 194R', 194G', 194B', 194R'', 194G'', 194B'', etc. of the light source modules 172, 172', 172'', etc. may be given a specific shape to improve performance of the illumination system 100. For example, one or more of the emitting surfaces may be shaped to match substantially the general shape of the illumination target 117. In particular, if the target 117 is a square entrance of a light tunnel, one or more of the emitting surfaces of the light source modules, such as 172, 172', 172'', also may be generally shaped as squares. If, on the other hand, the target 117 is a rectangular image-forming device or a rectangular color zone or pixel of an LCD, one or more of the emitting surfaces of the light source modules also may be generally shaped as rectangles. It will be readily understood by those of ordinary skill in the art that other shapes of the emitting surfaces and of the illumination targets are within the scope of the present disclosure.

Another exemplary embodiment of the illumination systems of the present disclosure is illustrated in Fig. 9. Such exemplary embodiments may be used for backlighting LCDs. The illumination system 200 includes one or more light source modules, exemplified by the light source modules 272 and 272', which may be three-chip LED modules, and a system of optical elements, such as a set of collimating lenses, exemplified by 211 and 211', in which each of the collimating lenses is associated with at least one of the light source modules. The illumination system 200 may be used to illuminate an imaging device 185. In such exemplary embodiments, sufficient amount of light source modules, exemplified by 272 and 272', having

emitting surfaces of different colors, exemplified by 294R, 294G, 294B and 294'R, 294'G, 294'B, should be used to cover a sufficient portion of the surface of the imaging device 185, which may be an LCD display, to obtain a resultant image of the desired size and quality. The imaging device may have an array of color zones or pixels, exemplified by the pixels 385R, 385G, 385B, 385'R, 385'G, 385'B and 385''R, 385''G, 385''B.

A lenticular array 165, including individual lenticules, such as 365, 365', 365'', which may be disposed proximate to the imaging device 185, may be used to image one or more of the emitting surfaces, such as 294R, 294G, 294B, 294'R, 294'G, 294'B, onto a corresponding color zone or pixel, such as 385R, 385G, 385B, 385'R, 385'G, 385'B, 385''R, 385''G and 385''B. The lenticules may be biconvex or plano-convex lenses. In some exemplary embodiments, one or more of the emitting surfaces may be imaged onto a filter stripe. In that case, each individual lenticule focuses the beams corresponding to different colors originating from different emitters to different places on the imaging device 185, for example, onto different color zones or pixels. In particular, the lenticule 365'' may focus the beams corresponding to red, green and blue light originating from the emitting surfaces 294R, 294G and 294B onto the color zones or pixels 385R'', 385G'' and 385B'' of the imaging device 185. Further, as it has been explained in connection with other exemplary embodiments, the shapes of the emitting surfaces may be matched to the shape of the color zones or pixels. Thus, each light source module may illuminate a predetermined area of the imaging device, containing many color zones or pixels, so that its effective surface is substantially lit. Uniformity is achieved by calibrating all the light emitting modules and their constituent multi-color emitters to the proper output level.

Referring further to Fig. 9, in some exemplary embodiments, the lenticular array 165 as well as the pixels or color zones, such as 385R, 385G, 385B, 385'R, 385'G, 385'B, 385''R, 385''G, 385''B, have a pitch of about 0.2 mm. Light-emitting surfaces, such as 294B, 294G, 294R, can be emissive stripes, for example LED stripes, with about 0.4 mm center-to-center spacing. The collimating lenses, such as 211 and 211', can be carefully spliced together to create a uniform illumination beam, so that the imaging device 185 is lit substantially without interruption. Alternatively, the spacing between light-emitting surfaces can be about 0.6mm, with the pitch between the lenticules of about 0.3 mm and about 0.1 mm between color zones or pixels of the imaging device 185. The collimating lenses, such as 211, 211', and the associated light source modules, such as 272 and 272', may be hexagonally packed or packed into cartesian grid, as desired for a specific application.

With further reference to Fig. 9, the illumination system 200 yields beams that are angularly separated depending on their color. As a result, red light may be channeled through the red color zone or zones of an imaging device, and likewise blue and green light may be channeled through the blue and green color zones, respectively. Filters may or may not be used with such embodiments of the present disclosure, depending on the purity of channeling. Pure channeling, or channeling that is substantially free from crosstalk, may be achieved with some embodiments of the present disclosure, since specific color will be delivered to a specific pixel, for example, only red light passing through a red color zone. Further, the present disclosure allows utilization of light source modules, such as LED modules, for best far-field distribution of illumination.

The approach of the present disclosure simplifies designing illumination systems for a variety of specific applications and allows for many different configurations of light source modules, optics and imaging devices. Exemplary embodiments of the present disclosure are capable of collecting light from lambertian-type emitters, such as LEDs, more effectively than traditional systems. Thus, more light may be transmitted to the illumination target resulting in better overall efficiency. In addition, exemplary embodiments of the present disclosure may have better imaging characteristics. Furthermore, the present disclosure allows the creation of illumination systems that use fewer components, are compact, are versatile, and are easier and less expensive to manufacture.

Although the illumination systems of the present disclosure have been described with reference to specific exemplary embodiments, those of ordinary skill in the art will readily appreciate that changes and modifications may be made thereto without departing from the spirit and scope of the present invention. For example, dimensions and configurations of the systems of optical elements that are used in various embodiments of the present disclosure can vary depending on the specific application and the nature and dimensions of the illumination target. In addition, the exemplary embodiments of the present disclosure may incorporate optical elements, components and systems described in U.S. Application entitled "Illumination System," Attorney Docket No. 59373US002, and U.S. Application entitled "Reshaping Light Source Modules," Attorney Docket No. 59526US002, filed concurrently herewith, the disclosures of which are hereby incorporated by reference herein to the extent they are not inconsistent with the present disclosure. Further, the present disclosure contemplates inclusion of additional optical elements into exemplary embodiments of the

illumination systems constructed in accordance with the present disclosure, as would be known to those of ordinary skill in the art.

Further, those of ordinary skill in the art will readily appreciate that embodiments of the present disclosure may be used with a variety of light sources, including white LEDs, color LEDs (e.g., red, blue, green or other colors) and multi-chip LED modules, e.g., RGB LED modules. RGB LEDs typically will allow achieving the best color performance, but white LEDs are acceptable for many applications.